Faculty and Researcher Publications

1995

Ultra-short pulse free electron laser oscillators

Blau, J.

Nuclear Instruments and Methods in Physics Research A, Volume 358, (1995), pp. 441-443

http://hdl.handle.net/10945/44059

ELSEVIER

Nuclear Instruments and Methods in Physics Research A 358 (1995) 441–443

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

Ultra-short pulse free electron laser oscillators

J. Blau *, R.K. Wong, W.B. Colson

Physics Department, Naval Postgraduate School, Monterey, California, USA

Abstract

An RF linear accelerator can produce ultra-short electron pulses on the order of a picosecond. In a long wavelength FEL, the pulse length can be much less than the slippage distance. Simulations show the effects of such short pulses on weak-field gain, saturated power, and optical pulse structure.

In a free electron laser (FEL) oscillator, the steady state optical pulse length depends on the electron pulse length, but it can be shorter or longer. Other factors such as the cavity Q and desynchronism affect the steady state optical pulse shape. The FEL weak-field gain and saturated power also depend on the electron pulse length.

It is important to compare the electron pulse length to the slippage distance, $N\lambda$, where N is the number of undulator periods and λ is the optical wavelength. This corresponds to the distance that the slower-moving electron pulse slips back relative to the optical pulse over one pass through the undulator. The slippage distance is typically a few hundred microns, but for a long wavelength FEL it can be greater than a millimeter.

When the electron micropulse length l_e is less than or equal to the slippage distance, short pulse effects dominate the FEL interaction [1]. Reduced overlap between the electron and optical pulses decreases the weak-field gain. The electron pulse amplifies the trailing edge of the optical pulse, reducing its effective group velocity, and the optical pulse drifts away from the electron pulse over many passes. To counteract this lethargy, the optical cavity length S is shortened by a desynchronism distance, $d = \Delta S/N\lambda$. If d is too large, the optical pulse eventually moves ahead of the electron pulse and decays according to the cavity Q, resulting in a broad optical pulse with small amplitude. When d is much smaller, the optical power can be large, and the optical pulse may be modulated due to the trapped particle instability [1].

An RF linac, such as the Stanford SCA, can produce ultra-short electron micropulses, with length $l_e \lesssim 1$ mm. For an FEL operating in the mid to far-IR, this pulse length can be much less than the slippage distance. In that case, the dimensionless electron pulse length $\sigma_z = l_e/N\lambda \ll 1$. For example, the FOM FELIX [2] and the Stanford FIREFLY [3] experiments propose to use $\sigma_z \simeq 0.1$–1.0.

Fig. 1 shows the results of a longitudinal multi-mode simulation of an ultra-short pulse FEL with $\sigma_z = 0.1$. The chosen desynchronism was $d = 0.002$, and the cavity $Q = 30$. The simulation was run for 1000 passes. The power evolution $P(n)$ is shown in the lower-right corner. The graph in the lower-left corner shows the electron pulse current density $j(z)$ at the beginning ($\tau = 0$) and end ($\tau = 1$) of the undulator, displaced by the slippage length $\Delta z = 1$. Above is an intensity plot of the optical pulse evolution $|a(z, n)|$, with the scale shown at the top. In the upper-left is the final optical pulse $|a(z)|$, which is longer than the electron pulse length, but shorter than the slippage distance. In the middle is shown the weak-field gain spectrum $G(\nu)$, the evolution of the optical power spectrum $P(\nu, n)$, and the final spectrum $P(\nu)$. On the right is shown the evolution of the electron spectrum $f(\nu, n)$.

The optical pulse evolution $|a(z, n)|$ shows a primary pulse moving ahead due to the desynchronism. As the power grows, the electrons overbunch, causing absorption of light on the trailing edge of the pulse. Meanwhile, a new smaller pulse begins to form and grow behind the primary pulse. If the simulation was carried out farther, it would show a train of subpulses forming, advancing according to the desynchronism, and decaying according to the Q. This would also cause an oscillation of the optical power $P(n)$. Such limit cycle behavior has been observed in previous simulations and experiments [4,5].

Fig. 2 shows the results of another simulation with a smaller desynchronism $d = 0.0002$ and a larger $Q = 100$. The final optical pulse $|a(z)|$ is now about the same length as the electron pulse $j(z)$, and much shorter than the slippage distance. Since the optical pulse is so short, the electron pulse does not "see" much of the light until it is more than halfway down the undulator, leaving less time

* Corresponding author. Tel. +1 408 656 2886, fax +1 408 656 2834, e-mail: blau@nps.navy.mil.

SSDI 0168-9002(94)01270-9

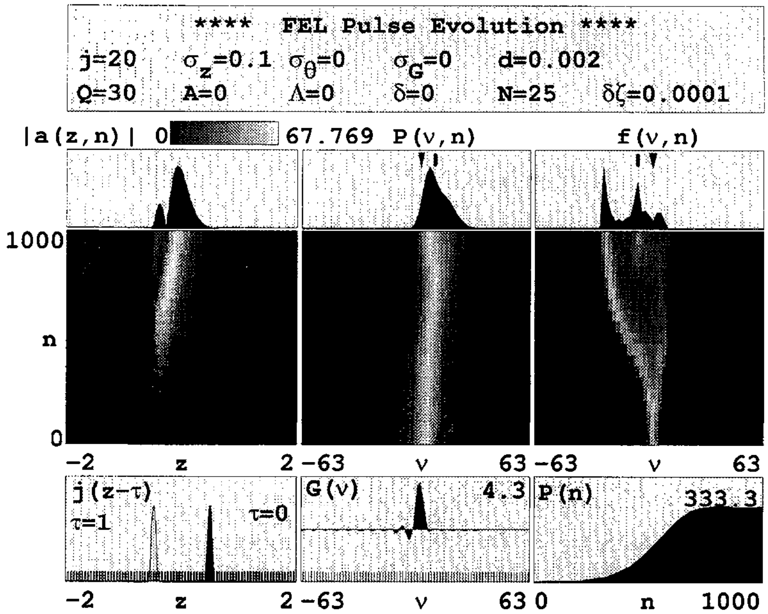

Fig. 1. Multi-pass evolution of an ultra-short pulse oscillator, $Q = 30$.

for bunching and gain. However, the large dimensionless current density $j = 20$ allows bunching and gain to develop quickly, and the optical field grows to a large amplitude.

Fig. 3 shows the weak-field gain versus the electron pulse length, for fixed $Q = 30$ and various values of desynchronism d. The total microbunch charge $j\sigma_z = 2$ is kept constant as the pulse length σ_z is reduced. It might be expected that the gain would remain constant, or even decrease slightly, as the pulse length is reduced, because of reduced pulse overlap. However, the simulations show that the gain actually increases slightly as the pulse length is reduced. This was also predicted in previous simulations done at FOM FELIX [6]. Here we show that the trend remains the same as desynchronism is varied, although the slope is greater as d is increased.

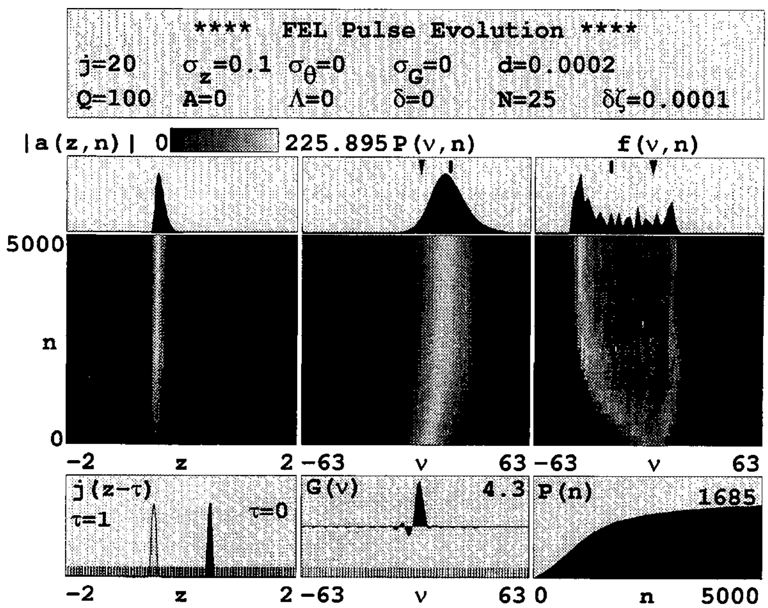

Fig. 2. Multi-pass evolution of an ultra-short pulse oscillator, $Q = 100$.

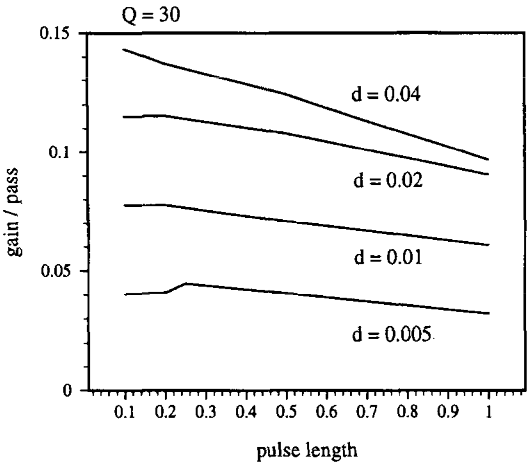

Fig. 3. Weak-field gain versus pulse length, for various values of desynchronism d.

Fig. 4 shows the saturated power versus electron pulse length, for $Q = 30$. Again, the total micropulse charge is kept constant as the pulse length is reduced. The desynchronism values shown here are smaller than the previous figure, because the optimum desynchronism is smaller when the field has reached saturation. For values of desynchronism $d > 0.003$, the saturated power is approximately constant as the pulse length is varied, in agreement with previous results [7]. However, when the FEL is operated near the peak of the desynchronism curve, $d = 0.002$, the power actually increases as the pulse length is reduced. The ripples in the curve are due to saturation and limit cycle effects.

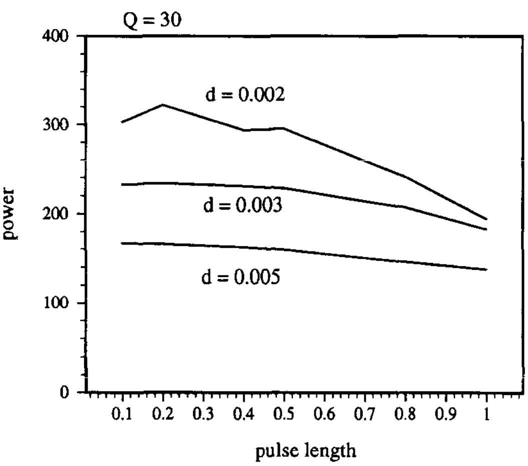

Fig. 4. Saturated power versus pulse length, for various values of desynchronism d.

A comparison was also made of parabolic and Gaussian electron pulses. For short pulses ($\sigma_z \leq 1$), there was very little change in the final saturated power and optical pulse shape.

Acknowledgements

The authors are grateful for support of this work by the Naval Postgraduate School, Stanford University (N00014-91-C-0170), and SURA/CEBAF.

References

[1] W.B. Colson, in: Free Electron Laser Handbook, eds. W.B. Colson, C. Pellegrini and A. Renieri (Elsevier, Amsterdam, 1990) chap 5.
[2] P.W. van Amersfoort et al., Nucl. Instr. and Meth. A 318 (1992) 42.
[3] T.I. Smith et al., presented at this Conference (16th Int. Free Electron Laser Conf., Stanford, CA, USA, 1994).
[4] D.A. Jaroszynski et al., Nucl. Instr. and Meth. A 331 (1993) 52.
[5] G.A. Cord, W.B. Colson and J. Frisch, Nucl. Instr. and Meth. A 304 (1991) 601.
[6] D.A. Jaroszynski et al., Nucl. Instr. and Meth. A 296 (1990) 480.
[7] D.A. Jaroszynski et al., Nucl. Instr. and Meth. A 318 (1992) 582.